

Imaging polarimetry of the rotating Bok globule CB67

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Abstract

Polarimetric observations of about 50 stars located in a close vicinity of the Bok globule CB67 having significantly nonspherical shape and rapid rotation are performed. The data obtained are compared with the available observations of this globule at radio and submillimeter wavelengths as well as some theoretical calculations. It is found that the elongation and the rotation moment of CB67 are oriented rather perpendicular to the magnetic fields, which is unusual for Bok globules and is difficult to be explained from the theoretical point of view.

Keywords: Bok globules, polarimetry, interstellar magnetic fields

1. Introduction

The Bok globules are known to be small molecular clouds where low mass stars are formed. Despite a long interest in these rather simple objects, details of the star formation process in them are not well known (see, for example, [1, 2, 3]). Undoubtedly, the magnetic fields and to some extent rotation should play an important role in the evolution of the globules [4]. However, detailed observational data are still required for more adequate understanding of the low mass star formation.

Observations of polarization of background stars is the basic way to study the magnetic fields in the vicinity and outer layers of such clouds [5]. Though the first polarization maps of Bok globules were obtained in the mid-eighties, only in a few cases the data were sufficiently detailed (the number of stars was about 30 or more). Like for more massive clouds the polarization maps of globules have shown different behavior of the magnetic fields (see for more details [1]). The connection of the magnetic fields in the outer regions of globules with those in their cores has been investigated by using the polarization maps at submillimeter wavelengths [6].

Information about angular velocity and the kind of rotation has also been obtained only for a few Bok globules (see, for example, [7, 8]). The magnetic fields and rotation of globules were observationally considered only by Kane and Clemens [9]. Using polarization maps obtained for 6 globules with known rotation (the maps were not presented in the paper), they concluded that the magnetic fields, the rotation axis and the Galactic plane direction tend to be parallel. Note that for all these globules the angle between the mean magnetic fields and the rotation axis did not exceed 50°.

In this paper a polarization map obtained by us for the rapidly rotating Bok globule CB67 is presented. In Sect. 2 and 3 the basic information about this cloud is given and the polarimetric data derived for about 50 stars in its field are described. In Sect. 4 we discuss the obtained results and point out that they are untypical of globules.

2. Object

CB67 (L31) is a small isolated globule (the center position: $l \approx 1^\circ, b \approx +16^\circ$) in the complex of molecular clouds in Ophiuchus which is located at the distance of about ~ 120 pc [10]. The angular size of this globule on the POSS maps is $16' \times 4'$, the position angle (hereafter all position angles are given in the equatorial coordinates) of the large semiaxis equals about 110° [11], the opacity class is 6 [12].

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The globule has been observed in CO, ^{13}CO , C^{18}O and OH lines. These observations have shown that the globule velocity is about 4.7 km/s with the velocity dispersions $\sigma_v(\text{CO}) \approx 1.3$ km/s and $\sigma_v(^{13}\text{CO}) \approx 0.9$ km/s. CB67 has the rapid differential rotation with the velocity gradient $\nabla v \approx 2$ km/s/pc, the angular velocity $\omega = 7 \cdot 10^{-14} \text{ s}^{-1}$ and the positional angle of the rotation axis of $\theta_J = 112 \pm 1^\circ$ [7]. The parameters of two cores which were observed in ^{13}CO line are similar: the size is about $14' \times 5'$, the density $n(\text{H}_2) \approx 3 \cdot 10^3 \text{ cm}^{-3}$ and the mass $M \approx 7\text{--}8 M_\odot$ [13].

Infrared observation did not reveal protostellar sources in this globule [14]. Visser et al. have investigated CB67 at submillimeter wavelengths and shown that the emission region at $850 \mu\text{m}$ has the approximate size of $11' \times 1.5'$ and mass of $2.2 M_\odot$ [15]. Note that these authors observed only a part (approximately a half) of the globule, and the region of cold dust emission looks like a filament with the typical diameter of about 0.06 pc [16].

So, the shape, size, location in the sky and other characteristics of CB67 seem to be rather typical of Bok globules.

The large- and small-scale geometries of the Galactic magnetic field are not yet well known [17, 18]. According to the standard stellar polarization data set given by Heiles' catalog [19], the Galactic magnetic field component \vec{B}_\perp forms a large arc including the points $(l, b) = (300^\circ, 0^\circ), (330^\circ, -15^\circ), (360^\circ, 0^\circ)$. So, in the Galactic plane below CB67 ($l = 0^\circ, b = -5^\circ - 5^\circ$) the mean position angle of stellar polarization is about 170° .

The globule CB67 is close to the ring-shaped interface between the Local Bubble and Loop I Bubble at the distance 70–280 pc [20]. The polarization of stars in the area of this interface was studied by Santos et al. [21]. They found that the polarization position angle in their field A2 ($l = 355 - 15^\circ, b = 20 - 35^\circ$) varied from about 50 to 150° with the preferable direction in a part of the interface ($l \approx 355 - 10^\circ, b \approx 17 - 20^\circ$) most close to CB67 being characterized by $\theta \sim 65^\circ$.

The stellar polarization data given by Heiles [19] for the field $l = 350 - 10^\circ, b = 7 - 27^\circ$ including the Ophiuchus cloud complex were analyzed by Li et al. [22]. They found that the mean polarization was nearly parallel to the “main filament” with the position angle being equal to $62 \pm 26^\circ$, which generally agrees with the polarization in the interface region obtained in [21]. Using the same polarization data source, we have considered the stellar polarization in a 7° radius circle around CB67. The position angle distribution is given in Fig. 1. The mean value equal to $60 \pm 15^\circ$ well agrees with the results described above.

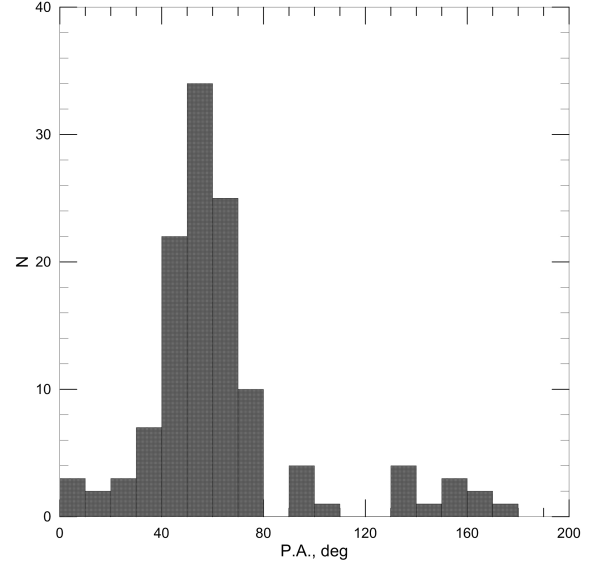


Figure 1: Distribution of the position angle of polarization of stars in a 7° radius circle around CB67 according to Heiles' catalog [19].

Thus, we conclude that the positional angle of the mean Galactic magnetic field component \vec{B}_\perp in the Ophiuchus cloud complex and in the Local Bubble – Loop I Bubble interface close to CB67 is about 60° , which does not strongly differ from the direction of the Galactic plane characterized by $\theta_G = 38.5^\circ$.

3. Observations

We performed polarimetric observations of stars in the vicinity of CB67 using the 2-meter telescope of Girawali observatory (IUCAA) in Pune (India) on March 12–14, 2013. The IUCAA Faint Object Spectrograph and Camera (IFOSC) and the imaging polarimeter IM-POL [23, 24] were used, the field of view had the diameter of $4'$, the wavelength range was $0.35\text{--}0.8 \mu\text{m}$. Some more details and references to the description of the camera work in the polarization mode can be found in [25].

For the polarimetric standards HD94851 and HD43384, we performed observation in the B and V bands and obtained the following values of the polarization degree: $P_B = 0.065 \pm 0.05\%$ for the first star and $P_V = 2.936 \pm 0.019\%$ (with the position angle error of 0.2°) for the second star. These values well agree with data from the literature: $P_B = 0.057 \pm 0.18\%$ for HD94851 [26] and $P_V = 2.94 \pm 0.04\%$, $\theta_V = 169.8 \pm 0.7^\circ$ for HD43384 [27]. The position angle of the latter standard was used to calibrate the position angles of polarization observed.

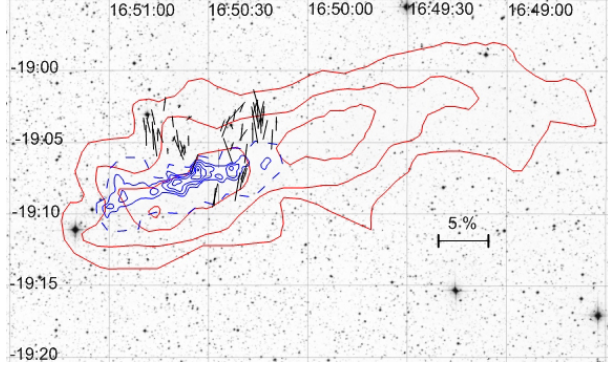


Figure 2: Polarization of stars in the region of CB67. The dotted lines show emission in the ^{13}CO line [13], the solid lines emission at $\lambda = 850 \mu\text{m}$ [15]. The dashed line confines the field observed in the submillimeter range.

The instrumental polarization of the IFOSC on the 2-m Giravali telescope has been monitored for many years and is known to be less than 0.05% (see, e.g., [28]), which is also confirmed by our results for the unpolarized standard. As the instrumental polarization is such small and does not behave like a systematic error, it is not being subtracted. Note also that our conclusions below are based on data with $P > 1\%$ when uncertainty of the position angle caused by the instrumental polarization should be below 1.5° .

Our polarimetric observations of three fields of $4'$ diameter were made without the use of any filters. Data were processed in the standard way. The results are presented in Fig. 2 where the polarization vectors for 49 stars (the vector length is proportional to the polarization degree) and contours of intensity in the ^{13}CO line [13] and at 850 micron [15] are shown. Table 1 contains the coordinates, polarization degree and position angle for the stars shown in Fig. 2.

Note that some of our stars are located in the region of CB67 that was considered by Kane and Clemens when they studied its rotation [7]. In Fig. 3 we present the figure from their paper after adding the vector of rotation moment, the line parallel to the Galactic plane, the polarization vectors for stars observed by us and the average direction of the magnetic fields near CB67 according to our results.

Using *JHK* data available for some of our stars in the Two-Micron All-Sky Survey catalog [29], we have roughly estimated the distances d and visual extinction A_V for about 20 stars observed (see Table 2) following the approach developed in [30]. For other our stars, either *JHK* data were absent, or $(J - K) > 0.75$, which makes such spectral class estimates less reliable. Two

Table 1: Polarization measurements of stars near CB67

No.	α , h	δ , deg	P , %	err $_P$, %	θ , deg	err $_\theta$, deg
1	16.840147	-19.061911	0.393	0.041	201.823	2.989
2	16.837495	-19.046930	2.111	0.074	174.043	1.010
3	16.837724	-19.056358	1.908	0.096	181.931	1.434
4	16.838400	-19.065884	2.039	0.180	180.529	2.526
5	16.839283	-19.066020	1.737	0.254	174.395	4.186
6	16.837975	-19.044588	2.844	0.242	181.629	2.441
7	16.837627	-19.043412	2.833	0.458	168.032	4.630
8	16.839890	-19.047447	1.065	0.305	170.202	8.194
9	16.840097	-19.084549	0.782	0.246	160.286	9.002
13	16.836435	-19.057038	1.330	0.540	178.830	11.641
15	16.839278	-19.039856	0.772	0.373	158.423	13.835
16	16.838130	-19.037979	1.726	0.500	160.545	8.301
17	16.837295	-19.062799	2.050	0.254	167.744	3.551
18	16.836777	-19.073952	2.054	0.814	176.928	11.360
19	16.839089	-19.070290	1.237	0.550	144.600	12.729
21	16.838930	-19.090313	1.996	0.587	172.756	8.426
22	16.840571	-19.085646	2.761	0.471	199.778	4.886
23	16.840515	-19.058644	2.312	0.895	159.596	11.085
24	16.840861	-19.060060	1.067	0.784	160.231	21.040
25	16.839561	-19.042167	3.009	0.972	138.034	9.253
26	16.838070	-19.032501	3.805	1.237	195.397	9.315
27	16.838316	-19.053435	4.020	2.120	189.485	15.108
28	16.838219	-19.042146	2.060	1.077	192.321	14.973
35	16.845459	-19.090318	0.403	0.023	182.582	1.600
36	16.847414	-19.057360	1.194	0.066	186.862	1.579
37	16.847092	-19.058471	1.511	0.066	193.316	1.250
38	16.846283	-19.070901	1.071	0.048	181.209	1.295
39	16.846108	-19.070207	1.493	0.095	198.818	1.821
40	16.846694	-19.049021	1.539	0.199	192.637	3.703
41	16.846694	-19.067703	2.977	0.382	182.964	3.677
42	16.843722	-19.077402	0.886	0.128	181.049	4.149
43	16.844296	-19.084957	1.497	0.320	196.845	6.119
44	16.844259	-19.090532	0.765	0.312	163.644	11.688
46	16.845681	-19.033881	1.378	0.563	171.910	11.707
47	16.846549	-19.076002	2.952	0.450	187.862	4.364
48	16.847249	-19.068779	2.174	0.591	181.334	7.790
49	16.844628	-19.084826	2.424	0.710	202.968	8.387
50	16.844639	-19.073954	1.943	0.950	187.438	14.004
51	16.845038	-19.055047	1.050	0.761	186.038	20.759
52	16.839006	-19.116860	1.491	0.632	162.659	12.136
53	16.839593	-19.127341	3.056	0.551	170.128	5.161
54	16.839267	-19.122442	1.876	0.787	170.271	12.016
55	16.839034	-19.112131	1.711	0.563	158.491	9.422
56	16.841444	-19.138138	2.555	0.691	167.358	7.753
57	16.841530	-19.141177	1.813	0.836	175.973	13.211
58	16.843146	-19.102738	2.157	0.811	159.042	10.765

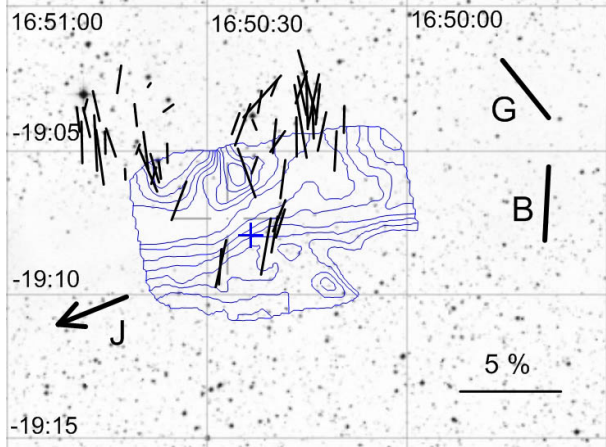


Figure 3: Rotation of CB67 according to [7]. The solid lines are contours of the mean radial velocity. Location of the center of motion (the peak of ^{13}CO integrated intensity) is given by the cross. The projected angular momentum \vec{J} , the Galactic plane direction \vec{G} , and the average magnetic field direction \vec{B}_\perp are presented by the corresponding vectors. Polarization of the stars observed is also given.

stars (N 29 and 32) were not included in Table 1 and our figures shown above because of their large polarization errors: $P = 0.4 \pm 1.8\%$ for N 29 and $P = 0.8 \pm 1.3\%$ for N 32. The values of A_V were also estimated utilizing the extinction map obtained from 2MASS data with the NICE technique in [31]. A weak correlation of two extinction estimates given in Table 2 can be seen.

Using Table 2 we produced Fig.4 that shows the dependences of P and P/A_V on A_V . Excluding the stars N 27 and 40 for which we probably derive too low extinction $A_V = 0.18$, our Fig.4 demonstrates the trends typical of other globules (see, e.g., [32, 28]): 1) a growth of maximum of the polarization degree P (in percent) with A_V (in mag.) so that $P < 2A_V$; 2) a decrease of maximum of the polarization efficiency P/A_V with A_V so that $P/A_V < -1.5A_V + 5$. Note that as the wavelength λ_{max} of maximum polarization P_{max} for stars such close to globules usually is in the interval about $0.5\text{--}0.65\ \mu\text{m}$ (e.g., [28]) and for the standard Serkowski law of the wavelength dependence of interstellar polarization in the interval $\lambda/\lambda_{\text{max}} = 0.75\text{--}1.3$ the values of $P(\lambda)$ differ from P_{max} by less than 10%, we probably have $P \approx P_{\text{max}} \approx P_V$ where P is the polarization degree derived by us without a filter in the instrument range $0.35\text{--}0.80\ \mu\text{m}$. Note also that according to our estimates all stars in Table 2 except for N 29 are located at distances larger than ~ 400 pc as expected from a statistical point of view.

Table 2: Estimates of distance and visual extinction from JHK photometry

No.	$P, \%$	J	H	K	d, pc	A_V, mag	$A_V, \text{mag [31]}$
1	0.39%	10.416	10.096	9.901	400	2.18	1.71
7	2.83%	14.343	13.827	13.608	1010	2.14	1.61
9	0.78%	13.148	12.805	12.632	1030	1.65	1.87
15	0.77%	13.855	13.285	13.129	560	0.41	1.55
23	2.31%	14.775	14.308	14.091	1560	2.25	1.61
27	4.02%	15.549	15.137	15.002	1600	0.69	1.63
29	0.39%	8.649	8.346	8.251	95	0.18	0.81
32	0.77%	10.680	10.327	10.152	360	1.67	1.46
37	1.51%	13.235	12.690	12.530	460	0.69	0.92
40	1.54%	14.063	13.597	13.473	730	0.18	0.81
41	2.98%	14.691	14.236	14.021	1600	2.24	0.97
43	1.50%	15.227	14.744	14.486	2260	3.01	1.46
48	2.17%	14.407	14.079	13.943	1650	0.94	0.95
49	2.42%	15.349	15.031	14.901	2730	0.89	1.40
50	1.94%	15.32	14.864	14.684	1630	1.55	1.33
51	1.05%	15.177	14.603	14.441	1010	0.54	1.14
53	3.06%	14.287	13.747	13.541	770	1.80	1.55
57	1.81%	14.328	13.857	13.681	930	1.35	1.79

4. Discussion

Figure 3 shows that the vectors of observed polarization are oriented rather uniformly in the field of CB67. It is better seen in Figs. 5–6 where we present some distributions over the position angle. Note that the polarization degree is mainly within the range $0.8\text{--}3\%$ and the position angle θ in the interval $150\text{--}200^\circ$, with the average position angle being $\bar{\theta} = 176.7^\circ$ and the dispersion $\sigma_\theta = 14.8^\circ$.

The distribution of stars over θ is rather typical of globules (see, for example, a similar distribution for globule B227 in [28]). Note, however, that there are many globules where the distribution of polarization vectors is not such uniform [9].

The important question is where the polarization we observe is originated? Generally, stellar polarization can provide information about the magnetic fields in dusty media located foreground or background of a cloud complex or within the complex but not physically related to the cloud studied.

A study of stellar polarization performed in [21] has shown that for their field I2 corresponding to the Ophiuchus molecular cloud complex for all (about couple of dozens) stars at the distance $d < 100$ pc one has the po-

larization degree $P < 0.05\%$, and for stars at $d > 120$ pc P is in the interval 0–2%. As for all (except for two) stars observed we got $P > 0.8\%$ we can conclude that the contribution of the foreground material to observed polarization should be negligible in the case of CB67.

The foreground polarization can be estimated for more directions from a relation between the interstellar extinction and polarization. But both the estimates based on Strömgren photometry and Hipparcos parallaxes in [33] and those derived from interstellar lines of Na I and Ca II in [34] do not show any significant extinction in the direction of $l \approx 0^\circ$ up to about 100 pc where the Ophiuchus cloud complex appears.

The contribution of background polarization hardly can be well estimated. The line of sight to CB67 ($l \approx 1^\circ, b \approx 16^\circ$) is directed generally above the Galactic center. Looking in the Galactic plane we see the Carina-Sagittarius arm at d about 0.7–1.4 kpc and the Crux-Scutum arm at d about 3 kpc. As Table 2 predicts the stars observed should mainly belong to the interarm space and the Carina-Sagittarius arm. As the CB67 latitude is high enough we can agree with [22] that there should not be much diffuse dust outside the Ophiuchus molecular cloud complex to produce essential interstellar (extinction and) polarization. Additionally, all dark clouds with the estimated distance in the field of the Ophiuchus complex have $d \sim 150$ pc (see, e.g., [35] and references therein), and there are no signs that another more distant dense cloud is projected on the CB67 region.

Considering emission in the ^{13}CO line studied in [13], we see that the stars observed are projected well inside the contours related with CB67 (see Fig. 2). Additionally, about 1/3 of our stars is projected on the contours of the systematic motion (rotation) of CB67 observed in [7]. Obviously, this denser gas and the dust mainly responsible for the observed polarization should spatially coincide. A weaker argument for the relation of the polarization with CB67 is that the dependences P vs. A_V and P/A_V vs. A_V presented in Fig. 4 well resemble those obtained for similar dense clouds.

Thus, we assume that the mean direction of observed polarization characterizes the magnetic field in the vicinity of CB67, and its position angle θ_B is equal to $\bar{\theta}$ obtained above. Then it is a bit unexpected that from our analysis in Sect. 2 it follows that the direction of the local field component \vec{B}_\perp near CB67 ($\theta_B = 177^\circ$) is parallel to the global field in the Galactic plane ($\theta \approx 170^\circ$) and nearly perpendicular to the magnetic field in the Local Bubble and Loop I Bubble interface ($\theta \approx 60 - 65^\circ$) being very close spatially to CB67.

Now it is interesting to compare 4 directions in the

case of CB67: those of the average magnetic fields in the close vicinity of the globule (according to our results its position angle is $\theta_B = 177 \pm 15^\circ$), the rotational angular momentum ($\theta_J = 112 \pm 1^\circ$ [7]), the Galactic plane ($\theta_G = 38^\circ$) and the elongation of the globule image on the ^{13}CO maps [13] ($\theta_x^{\text{CO}} = 110 \pm 7^\circ$). The directions of the largest extension in visual and at submillimeter wavelengths have similar values: $\theta_x^{\text{vis}} = 110^\circ$ and $\theta_x^{\text{submm}} = 104^\circ$, respectively. Note that according to Li et al. (2013) the direction of “the main filament” of the Ophiuchus molecular cloud complex has $\theta_{\text{fil}} = 70 \pm 12^\circ$.

For CB67, the difference $|\theta_B - \theta_x| = 67 \pm 13^\circ$ is rather close to 90° . For other extended molecular clouds, this difference is close to either 0 or 90° [1]. Li et al. [22] have considered 12 cloud complexes, entering into the Gould belt, and found that the main filament direction and the average magnetic field one differ by either less than 10° (4 complexes), or more than 70° (7 complexes, and in 5 cases this difference exceeds 85°). On other side, Ward-Thompson et al. [6] have noted that in the cores of low mass molecular clouds (7 ones were considered) the difference of the small semiaxis direction and the magnetic field one obtained from submillimetric polarimetry data is about 30° with a small dispersion. If the field inside CB67 were parallel to that in its vicinity, we would have $|\theta_B^{\text{submm}} - \theta_y^{\text{submm}}| \approx 15^\circ$.

We get $|\theta_J - \theta_G| \approx 30 \pm 1^\circ$. Note that Kane and Clemens [7] have considered 14 globules and found that this difference takes values from 0 to 90° with approximately equal probability, though the values in the range $40\text{--}50^\circ$ may be a bit more probable.

The difference $|\theta_B - \theta_J| = 65 \pm 15^\circ$ is remarkable. So far only Kane and Clemens have systematically compared polarization maps and rotation of globules [9]. They found that for 5 out of the 6 globules studied the primary magnetic field direction was aligned with the projected rotational axis, and the difference $|\theta_B - \theta_J|$ was less than 20° . These 5 globules included CB4 and CB17 with uniform and well aligned magnetic fields nearly parallel to the Galactic plane (all like in our case of CB67) and CB161, CB195, CB228 with a bimodal distribution of polarization position angles. Kane and Clemens further suggest that some (primary) polarization traces the field local to the globules, while other polarization traces the field at some distance away from (most likely behind) the globules. The secondary polarization usually appears to follow the Galactic plane. The notable case is CB183 where two equally strong components are observed one of which follows the Galactic plane while another does not coincide with either magnetic field component. The authors conclude that CB183 may not be a simple singly condensed globule,

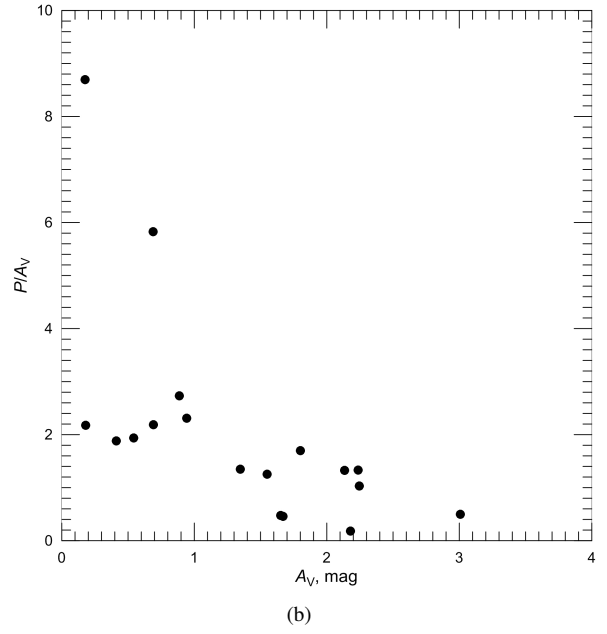
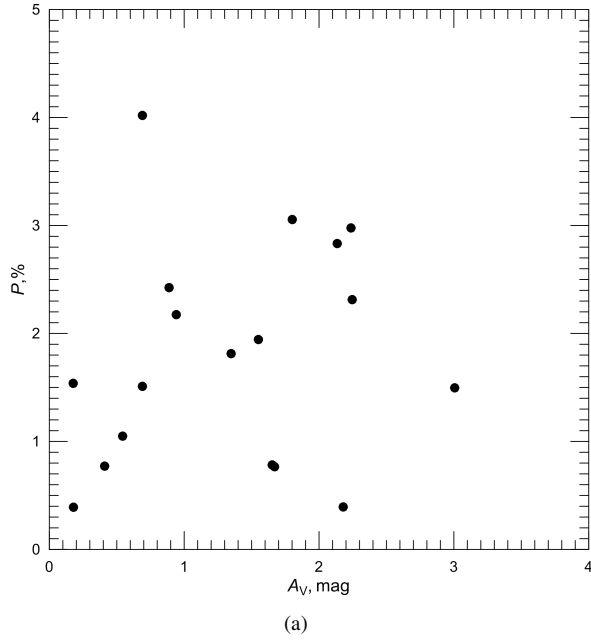


Figure 4: Dependence of polarization degree P on visual extinction A_V (a) and dependence of polarization efficiency P/A_V on A_V (b) for some stars near CB67

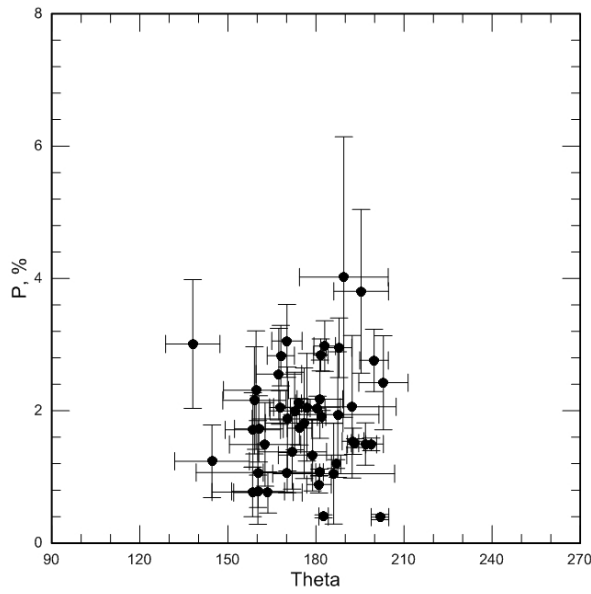


Figure 5: Polarization degree P in dependence on the positional angle θ for all stars observed.

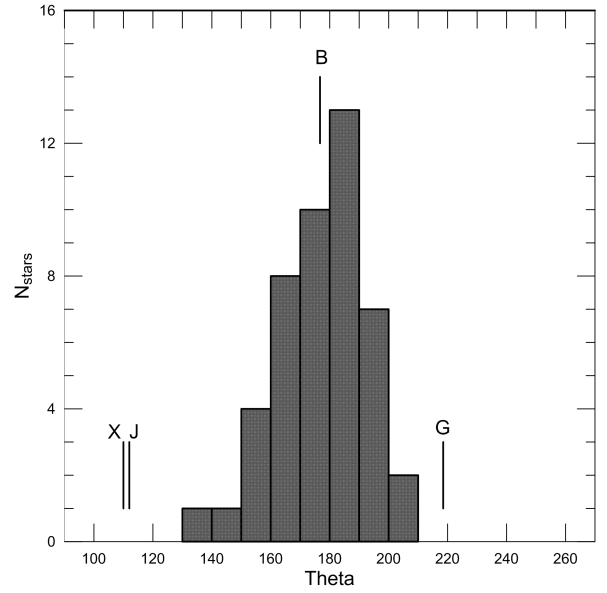


Figure 6: The distribution of all stars observed over θ . The labels show the position angles of the largest extension in visual (X), the angular moment (J), the Galactic plane (G), and the mean magnetic field (B).

but a conglomeration of condensations.

The theoretical papers mainly included MHD calculations of collapse for rotating spherical clouds when the magnetic fields and the rotation axis are parallel and very seldom when they are not [36]. In the latter case a disk is formed and its angular rotation moment tends to be parallel either to the magnetic fields or to the rotation axis of the cloud depending on the relative strength of the fields (see, for example, [37]).

The situation observed for CB67 when the cloud (core) is extended and rotates around an axis which is almost perpendicular to the magnetic field direction does not fit the theoretical modeling.

5. Conclusions

On the basis of polarimetric observations of about 50 stars located in the vicinity of the Bok globule CB67 the orientation of the magnetic fields near and in the outer layers of this cloud has been considered. It is found that the globule and its core are extended and rotate around the axis that makes the angle of about 70° with the magnetic field direction. This situation is unusual for globules and can be hardly explained in the framework of MHD calculations of collapse of a low mass cloud.

The authors are thankful to an anonymous referee for useful remarks which helped considerably to improve the manuscript.

The authors thank Inter University of Center for Astronomy and Astrophysics, Pune, India for allotment of telescope time for doing this work.

This work was supported by the joint RFBR and DST (India) Grant 11-02-92695 (RUSP 1110) which supported an Russia–India scientific collaboration, the RFBR Grant 13-02-00138 and a Grant of the Minobrnayka of Russia within the state assignment for SUAI in 2013–14.

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